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*Published in:*  
Journal of Hydrology

*Link to article, DOI:*  
[10.1016/j.jhydrol.2015.08.047](https://doi.org/10.1016/j.jhydrol.2015.08.047)

*Publication date:*  
2015

*Document Version*  
Peer reviewed version

[Link back to DTU Orbit](#)

*Citation (APA):*  
Locatelli, L., Mark, O., Mikkelsen, P. S., Arnbjerg-Nielsen, K., Wong, T., & Binning, P. J. (2015). Determining the extent of groundwater interference on the performance of infiltration trenches. *Journal of Hydrology*, 529, 1360-1372. <https://doi.org/10.1016/j.jhydrol.2015.08.047>

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1    **Determining the extent of groundwater interference on the performance of**  
2    **infiltration trenches**

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16    **ABSTRACT**

17    Infiltration trenches are widely used in stormwater management, but their capacity decreases when  
18    installed in areas with shallow groundwater where infiltration is limited by groundwater drainage.  
19    Here the hydrological performance of single infiltration trenches in areas with shallow water tables  
20    is quantified in terms of their capability to reduce peak flow, peak volume and annual stormwater  
21    runoff volume. To simulate the long term hydrological performance of infiltration trenches two  
22    different models are employed. The models continuously simulate infiltration rates from infiltration

trenches using a 19 year rainfall time series from Copenhagen as input. The annual and single event stormwater runoff reduction from infiltration trenches was determined for 9 different scenarios that covered different soil conditions and infiltration trench dimensions. Monte Carlo simulations were used in order to quantify the impact of parameter variability for each scenario. Statistical analysis of the continuous long term model simulations was used to quantify the hydrological performance of infiltration trenches. Results show that infiltration trenches are affected by groundwater when there is an unsaturated depth of less than 1.5-3 m in sandy loam, 6.5-8 m in silt loam and 11-12 m in silty clay loam. A correction factor that can be applied for infiltration trench design when there is a shallow groundwater table is presented. The analyses showed that below a certain value of unsaturated depth the dissipation capacity of the mound/groundwater becomes the dominant process determining the infiltration capacity from infiltration trenches. In these cases it is essential to consider the local groundwater conditions in the infiltration trench design process.

## **1. INTRODUCTION**

Infiltration trenches are employed in many countries for stormwater infiltration as part of Water Sensitive Urban Design (WSUD) which aims at improving urban stormwater management (Fletcher et al., 2014; Revitt et al., 2003; Wong and Brown, 2009). Infiltration trenches do not require the use of land surface areas which is a big advantage particularly in dense urban areas. However the city scale application of stormwater infiltration is constrained by the existing infrastructure and built environment, economical aspects, groundwater levels, local drinking water assets, soil pollution and stormwater runoff water quality (Göbel et al., 2004; Mikkelsen et al., 1994; Revitt et al., 2003).

Several studies have investigated the impact of widespread stormwater infiltration on the drainage system at the urban scale and shown an overall reduction of peak flows, stormwater runoff volume (Xiao et al., 2007; Holman-Dodds et al., 2003; Elliot et al., 2009), and combined sewer overflows (Roldin et al., 2012a; Peters et al., 2007). These studies agreed that the performance of infiltration systems is highly dependent on the local conditions, and particularly the physical properties of the

48 soil. However they did not explicitly account for the interaction of the infiltration system with  
49 groundwater.

50 Models are often used to evaluate infiltration trench performance and Elliott et al. (2007) presented  
51 a review of commercial software available for simulating the impact of WSUDs on the urban  
52 drainage system. Manglik et al. (2004) showed a method to quantify the groundwater response from  
53 multiple infiltration basins; Antia (2008) and Endreny and Collins (2009) showed case studies at the  
54 urban residential area scale; Maimone et al. (2011), Ku et al. (1992), Jeppesen (2010) and Göbel et  
55 al. (2004) presented case studies at the urban scale. These studies reached the conclusion that  
56 widespread stormwater infiltration increases groundwater levels and can create surface runoff,  
57 particularly for areas with poorly conductive soils and a shallow groundwater table; some of the  
58 studies recommended groundwater control strategies when planning for large scale stormwater  
59 infiltration.

60 A large number of studies have presented models to either design or predict infiltration rates from  
61 single infiltration trenches. Guo (1998) presented a steady-state surface-subsurface model to design  
62 trench infiltration basins taking into account the distance to the groundwater table; this model does  
63 consider the formation of mounds below the infiltration system, transient processes that affect the  
64 performances of the system and it neglects lateral infiltration from the basins. Dussaillant et al.  
65 (2004) presented a three layer model with subsurface flow described by Richards' equation for  
66 designing rain gardens; however this model also does not account for the formation of mounds  
67 below the infiltration unit. Browne et al. (2008) presented a one-dimensional model for infiltration  
68 rates from infiltration units that accounts for changing surrounding soil moisture conditions and the  
69 continuous interaction between storage and surrounding soil; this model does not consider variation  
70 in the depth of the saturated zone and horizontal infiltration from the sides of the infiltration unit.  
71 Browne et al. (2012) presented a two-dimensional model to calculate infiltration rates from  
72 stormwater infiltration systems but did not consider the effects of local mounds. Thompson et al.

73 (2010) used the software HYDRUS-2D to predict water-table mounding and the main factors  
74 affecting the watertable beneath infiltration basins and showed that mound heights increased as the  
75 thickness of both the unsaturated and saturated zones decreased and as the initial soil moisture,  
76 basin size and ponding depth increased. Carleton (2010) simulated the effect of stormwater  
77 infiltration from large basins on local groundwater mounding showing that analytical solutions  
78 based on the Hantush equation (Hantush, 1967) underestimate the maximum height of groundwater  
79 mounding by 15% when compared to finite-difference simulations. Roldin et al. (2013) presented a  
80 model to simulate the infiltration rates from single infiltration trenches in the presence of  
81 groundwater table showing that infiltration rates significantly reduce as the groundwater mound  
82 gets closer to the bottom of the infiltration trench.

83 Others have examined the performance of infiltration systems in field experiments. Bergman et al.  
84 (2011) and Warnars et al. (1999) collected data of inflow rates and water levels in experimental  
85 infiltration systems to estimate hydraulic conductivity and the development of clogging. Machusick  
86 et al. (2011) presented an equation describing the relationship between groundwater mounding,  
87 precipitation and groundwater temperature for a experimental field of approximately 0.5 ha.

88 None of the papers reviewed above employed long term model simulation to quantify how the  
89 hydrological performance of infiltration trenches is affected by the distance to the groundwater  
90 table. Such a quantification is important because infiltration trenches are intended to be a key  
91 element in water management of urban areas and so clear design rules should be available. Two  
92 different models were used, one that considers the interaction with groundwater and one that does  
93 not. The annual and single event stormwater runoff reductions from infiltration trenches were  
94 quantified for 9 different scenarios that covered common soil types and infiltration trench designs  
95 encountered in Denmark. This study also introduces a correction factor to be used in the design  
96 process of infiltration trenches in the presence of a shallow groundwater table. This factor can be  
97 used to correct the infiltration trench design volume to account for the effect of the distance

98 between the infiltration trench bottom and the groundwater. This factor is calculated for the 9  
99 different scenarios as a function of the distance between the infiltration trench bottom and the  
100 groundwater.

101 The results are intended to support practitioners and decision makers by quantifying key  
102 hydrological performances and improving the actual design of infiltration trenches in the presence  
103 of a shallow groundwater table.

## 104 **2. MATERIALS AND METHODS**

105 Figure 1 shows the system that is modeled in this paper. The infiltration trench has a width  $B$ , a  
106 height  $H$  and a length  $L$  (perpendicular to the drawing) and receives stormwater runoff from the  
107 connected impervious area. When the water level  $h$  in the infiltration trench is above 0, infiltration  
108 occurs and when  $h$  exceeds the infiltration trench height  $H$  overflow to the sewer system occurs.  
109 Infiltrated stormwater percolates and recharges the unconfined groundwater aquifer which has a  
110 saturated thickness  $h_s$ . The unsaturated distance between the bottom of the infiltration trench and  
111 the initial undisturbed groundwater table is here referred to as  $h_{us}$ . The height of the groundwater  
112 mound below the centerline of the infiltration trench is called  $d$ . The groundwater is assumed to  
113 have fixed head at a distance  $1/2 L_{drain}$  from the center of the infiltration trench.

### 114 **2.1 The infiltration trench models**

115 Two different models were used in this study. The first model was developed by Warnars et al.  
116 (1999) and Roldin et al. (2012b) and includes no groundwater interaction and so is referred to as the  
117 ‘Simple Model’ ( $SM$ ). The second model includes groundwater interaction (Roldin et al., 2013) and  
118 is here referred to as ‘Model with Mounding’ ( $MM$ ). Table 1 summarizes the parameters of the 2  
119 models.

120 The mass balance of the infiltration trench is the same in both models and is given by:

$$B \cdot L \cdot \varphi \cdot \frac{dh}{dt} - Q_{in} + Q_{out} = 0 \quad (1)$$

where  $B$  is the width of the infiltration trench,  $L$  is the length of the infiltration trench,  $\varphi$  is the porosity of the infiltration trench filling material,  $h$  is the water level in the infiltration trench,  $Q_{in}$  and  $Q_{out}$  are the inflow and outflow rates from the infiltration trench, and  $t$  is time. The outflow from the infiltration trench  $Q_{out}$  is:

$$Q_{out} = Q_{infiltration} + Q_{sewer} \quad (2)$$

where  $Q_{infiltration}$  is the infiltration rate and  $Q_{sewer}$  is the overflow rate to the sewer pipe.

The inflow to the infiltration trench  $Q_{in}$  is calculated as:

$$Q_{in} = ASR \cdot i \cdot (B \cdot H \cdot L \cdot \varphi) = Area \cdot i \cdot \varphi \quad (3)$$

where  $ASR$  (*Area/Storage Ratio*) is the design criteria defined as the connected impervious area per unit volume of infiltration trench [ $m^2/m^3$ ];  $i$  is the rain intensity,  $H$  the infiltration trench height and  $Area$  is the connected impervious area. Equation (3) is written as above because typical design procedures specify the *Area/Storage Ratio* for a given infiltration trench geometry  $BHL$ , return period and connected impervious area. Here an infiltration trench design was selected for a number of scenarios according to Danish design standards (Petersen et al., 1994, 1995). The designs for these scenarios aim at storing the stormwater volume accumulated during design events of a specified return period determined using the Danish regional IDF curves (Madsen et al., 2009).

The infiltration trench in this paper was assumed to be infinitely long (no flow in the longitudinal direction of the infiltration trench). This assumption produces an underestimation of the hydrological performance since in reality the flow is 3-dimensional and some water will infiltrate through the ends of the trench. The underestimation is negligible for infiltration trenches where the length  $L$  is large compared to the cross section  $BH$ . The porosity of the filling material was assumed to be  $\varphi=1$ , i.e. the simulations represent infiltration trenches with a modern filling material having a

144 very high porosity. Such porous filling material is commonly used in Danish infiltration trenches  
145 (Roldin et al., 2012a; Roldin et al., 2012b; Roldin et al., 2013) .

#### 146 ***The ‘Simple model’ (SM)***

147 The Simple Model is based on the infiltration trench mass balance (Eq. 1) and the infiltration rate  
148  $Q_{infiltrationSM}$  from the infiltration trench is calculated according to Eq. 4.

$$149 \quad Q_{infiltrationSM} = KBL + 2K(hL + hB) \quad (4)$$

150 Where  $B$  is the width of the infiltration trench,  $L$  is the length of the infiltration trench,  $h$  is the water  
151 level in the infiltration trench, and  $K$  is the saturated hydraulic conductivity. This study assumes  
152 isotropic, uniform and no-clogging conditions. This was done for simplicity and is justified by the  
153 fact that infiltration tests often do not distinguish between vertical and horizontal hydraulic  
154 conductivity, and guidelines like CIRIA (2007) suggest regular maintenance to ensure proper  
155 infiltration rates. However, other studies assumed no infiltration from the bottom in order to safely  
156 account for clogging. For example, Peters et al. (2007) measured infiltration rates through the sides  
157 to be 3-4 times bigger than bottom infiltration rates. Bergman et al. (2011) showed that clogging  
158 reduced initial infiltration rates of 2 infiltration trenches by a factor of 3-4 after 20 years of  
159 operation. Roldin et al. (2012a) used a horizontal hydraulic conductivity 2 times higher compared to  
160 the vertical. In this paper, horizontal and vertical hydraulic conductivity were gathered into a single  
161 parameter  $K$  which can be interpreted as an effective saturated hydraulic conductivity.

#### 162 ***The ‘Model with Mounding’ (MM)***

163 The Model with Mounding is based on the infiltration trench mass balance (Eq. 1) with the  
164 infiltration rate being modified according to Eq. (5).

$$165 \quad Q_{infiltrationMM} = \frac{\theta_s - \theta(h_{us} - d)}{\theta_s - \theta(h_{us})} \cdot Q_{infiltrationSM} \quad (5)$$



166 where  $\theta_s$  is the saturated moisture content,  $\theta(h_{us}-d)$  is the moisture content at the bottom of the  
167 infiltration trench and  $\theta(h_{us})$  is the moisture content at the bottom of the infiltration trench, which is  
168 located at the distance  $h_{us}$  above the groundwater table. Eq. (5) shows that the infiltration rate  
169 approaches that of the Simple Model (which is assumed to be equal to the hydraulic conductivity,  
170 i.e. a unit-gradient Darcy flux) when the mounding height  $d$  is small whereas it decreases as a  
171 function of the soil moisture retention curve and becomes 0 when the top of the mound  $d$  reaches  
172 the infiltration trench bottom (this means that the infiltration rate from the trench equals the  
173 groundwater mound dissipation rate when the mound approaches the bottom of the trench). In  
174 reality the mounding can grow up to the water level in the infiltration trench, this means that the  
175 infiltration in the Model with Mounding is underestimated especially when  $h_{us}$  approaches 0. In  
176 practice an infiltration trench with the bottom placed right at the ground water table height ( $h_{us} = 0$   
177 m) would infiltrate some water whereas it does not in the model *MM*.

178 The water content  $\theta$  is calculated according to the Van Genuchten soil moisture constitutive relation  
179 (Van Genuchten, 1980):

$$180 \quad \theta(\Psi) = \theta_r + \frac{\theta_s - \theta_r}{(1 + (\alpha|\Psi|)^n)^m} \quad (6)$$

181 where  $\theta_r$  is the residual moisture content,  $\theta_s$  is the saturated moisture content,  $\psi$  the pressure head  
182 and  $\alpha$ ,  $n$  and  $m$  are the specific soil parameters. Eq. (6) is applied with Eq. (5) using  $\psi = h_{us} - d$  (see  
183 Figure 1).

184 The depth of the mound in the model *MM* of Roldin et al. (2013) is calculated at each model time  
185 step using the analytical solution of the Hantush equation based on a finite Fourier sine transform  
186 series (Rao and Sharma, 1983). The depth of the mound is then used to calculate the infiltration  
187 rates in Eq. (5) in the following time step. The analytical solution is a 2D solution that computes the  
188 height of the groundwater throughout the  $L_{drain}$  domain and assumes a constant water level at the  
189 boundaries of the domain. This boundary can be interpreted as an open water body, a stream or a

190 drainage pipe. The extent of the drainage area is defined by the parameter  $L_{drain}$  and the  
191 groundwater domain is assumed to be symmetrical with respect to the center of the infiltration  
192 trench.

## 193 **2.2 Model scenarios**

194 The two different infiltration trench models discussed in Section 2.1 were used to run continuous  
195 simulations (transient simulations) of 19 years based on input rainfall data collected at a rain gauge  
196 in Copenhagen between 1992 and 2010 (the rainfall time series has a 1 minute time step).

197 Continuous simulations show the time development of the groundwater mound, the water content in  
198 the infiltration trench and the infiltration rates as a function of the input rainfall pattern and the  
199 other model parameters. The model time step was set to be 10 minutes. The time step is a  
200 compromise between calculation time and accuracy of the simulated 10 minute peak flow reduction  
201 shown in Section 2.3. Computing all the simulations with a 1 minute time step would require  
202 approx 90 days (using 9 processors) compared to 4 days when using a time step of 10 minutes. A  
203 comparison between simulation results using 1 and 10 minute model time steps was made for 50  
204 simulations (using the *SM*). The comparison showed that the 10 minute time step overestimates the  
205 resulting peak flow reductions by an average of 4%. Campisano et al. (2015) presented a thorough  
206 analysis considering several modeling time steps for rainwater tanks and showed less than 5%  
207 difference in peak flow reduction going from a 5 minute to a 15 minute time step.

208 The ‘Model with Mounding’ was run with a 3 year warm up period (3 years of warm up followed  
209 by 19 years of simulation) because the mound takes approximately 2 years to develop in the slowest  
210 scenarios (The initial conditions of the warm up period are an empty infiltration trench,  $h=0$  and a  
211 flat groundwater table  $d=0$ ). This suggests that the performance of infiltration trenches in areas  
212 affected by shallow groundwater decreases during the period immediately after the installation until  
213 the mound is fully established. The mound can develop in a few months in highly conductive soils,

214 while it can take several years in less conductive soils with a long drainage distance  $L_{drain}$ . The  
215 ‘Simple model’ was run with the same warm up period although this was not strictly necessary.  
216 9 different scenarios were run, each with approximately 1300 Monte Carlo simulations (tests  
217 showed that more than 1000 simulations were needed to obtain good results). The idea behind these  
218 scenarios was to cover typical soil types and different infiltration trench designs. The trench sized  
219 were defined to be ‘small’, ‘medium’ or ‘large’. The parameter space was sampled using Latin  
220 Hypercubic Sampling (Helton and Davis, 2003). The uncertainty (Zimerman, 2000) of the input  
221 parameters (due to measurement uncertainty, spatial variability and design choices) was assumed to  
222 have Normal, Log-normal and Uniform distribution depending on the parameters. The model  
223 scenarios (S1-S9) with a description of the input parameter uncertainty are summarized in Tables 2  
224 and 3.

225 Table 2 shows the *ASR* and the ‘Storage depth’ (defined as storage volume per impervious area or  
226 the inverse of *ASR*) for the scenarios considered. *B* and *H* were varied according to common trench  
227 geometries encountered in residential areas in Denmark.  $h_{us}$  was varied according to preliminary  
228 results which determined the range of  $h_{us}$  affecting the infiltration trench performance.  $h_s$  was  
229 assumed to vary between 1 and 10 meters in all the scenarios; this distance was chosen according to  
230 preliminary results which showed that the saturated depth mostly influenced the infiltration trench  
231 performance for  $h_s < 10\text{m}$ , however saturated thickness can be much larger (this means that results  
232 slightly underestimate actual infiltration trench performance).  $L_{drain}$  was assumed to vary between  
233 40 and 800 m.  $\frac{1}{2} L_{drain}$  physically represents the distance to a open water body, a stream, a drainage  
234 pipe, a foundation drain, or any other underground draining path that can be found in an urban area.  
235 This distance was selected after considering the work of Malaguerra et al. (2012) who showed that  
236 the median distance between thousands of drinking water wells in Denmark and streams is in the  
237 order of 450-500 m.

238 Three different soils were considered for the model scenarios (as shown in Table 2): loamy sand,  
239 silt loam and silty clay loam. The corresponding soil parameters were derived from Carsel et al.  
240 (1988) and are summarized in Table 3.

## 241 **2.3 Model outputs**

242 We analyze three different model outputs:

- 243 • Annual storm water runoff reduction
- 244 • Single event stormwater runoff peak reduction
- 245 • Single event stormwater runoff volume reduction

246 Here the stormwater runoff reduction is defined as:

$$247 \quad reduction = 100 \left( 1 - \frac{Q_{sewer}}{Q_{in}} \right) \quad [\%] \quad (7)$$

248 where  $Q_{in}$  is the storm water runoff inflow rate to the infiltration trench and  $Q_{sewer}$  is the overflow  
249 rate to the sewer pipe. Results for *reduction* are shown per unit length of infiltration trench.

250 The annual stormwater runoff reduction, defined as the ratio between the annual infiltrated  
251 stormwater volume and the annual stormwater inflow volume into the infiltration trench, was  
252 calculated for each model scenario and for each year of the 19 year continuous simulation. The  
253 results show the annual stormwater runoff reduction from the Monte Carlo simulations for both the  
254 *SM* and the *MM*. Therefore the results will include both the effect of the input parameter uncertainty  
255 and the inter-annual variability of annual stormwater runoff reduction.

256 Results are presented for two different cases, the case where groundwater does not affect the  
257 performance of infiltration trenches (*SM*), and the case where it does (*MM*). The definition of  
258 whether groundwater does or does not influence the infiltration trench performance was determined  
259 as follows. The annual stormwater runoff reduction was found as a function of the unsaturated  
260 depth (Model with Mounding) and then a threshold value above which the influence of unsaturated

261 depth becomes insignificant was determined. This threshold value was calculated for each scenario  
262 and was defined as the point where the mean annual runoff from the Model with Mounding equals  
263 95% of the mean annual runoff from the Simple Model.

264 For a better understanding of the uncertainty in the results, the annual stormwater runoff reduction  
265 was also determined as a function of the most sensitive parameters (unsaturated depth  $h_{us}$ , saturated  
266 depth  $h_s$ , length of the domain  $L_{drain}$  and infiltration trench cross section  $B$ ).

267 Single rainfall events are defined as being separated by dry weather of more than one hour duration.  
268 The single event peak flow and volume reductions were also calculated with both models. Single  
269 event peak reduction is defined as the ratio between the maximum single event 10 minutes overflow  
270 intensity from the infiltration trench (relative to the runoff area) and the maximum single event 10  
271 minutes rainfall intensity. Single event volume reduction is defined as the ratio between the single  
272 event overflow volume from the infiltration trench (relative to the runoff area) and the single event  
273 rainfall volume. Results are shown as a function of the rainfall return period and for each of the 9  
274 scenarios.

275 The single event peak and volume stormwater runoff reduction was obtained as follow:

- 276 • Compute the maximum 10 minute intensity and the total volume  $Q_{in}$  and overflow to the  
277 sewer for each event in the simulated time series.
- 278 • Sort the 10 minutes intensities and the total volume of  $Q_{in}$  and overflow per event in  
279 descending order.
- 280 • Calculate the single event peak reduction and the single event volume reduction as defined  
281 above.
- 282 • Assign to each reduction a return period  $T$  [years] calculated using the Weibull (1939)  
283 plotting position:

$$T = \frac{y+1}{r} \quad (8)$$

where  $y$  is the duration of the time series in years and  $r$  is the rank of the single rain event.

The results allow the calculation of the reduction for single rainfall events with a return period in the range of 5-10 and 0.5-1 years. 0.5-1 year return period events typically cause CSOs and sewer surcharge, and 5-10 years is the common design return period adopted in Denmark for urban drainage infrastructure.

### **Sensitivity analysis**

A sensitivity analysis was carried out for the 9 scenarios and the two models using linear regression of Monte Carlo simulations (Sin et al., 2010) for the ‘annual stormwater runoff reduction’. The results show the standardized regression coefficients (Sin et al., 2010) for the parameters of the two models.

### **2.4 Correction factor**

An empirical correction factor to be applied to the designed infiltration trench volume is proposed. Common tools available to design infiltration trenches use simple models that assume infiltration rates similar to Equation 4. The infiltration rates from such models are a function of the infiltration trench geometry and soil hydraulic conductivity. Nevertheless the formation of mounds reduces infiltration rates. We therefore present a correction factor  $\beta$  to calculate a corrected infiltration trench volume per unit length of infiltration trench  $BH_1$  for cases influenced by mounding.

$$BH_1 = \beta \cdot BH \cdot \varphi \quad (9)$$

The correction factor will be presented as a function of unsaturated depth  $h_{us}$  for the 9 scenarios introduced in Section 2.3, and  $BH$  is the infiltration trench cross section volume per unit length.  $\beta$  is calculated using the Model with Mounding and with the following procedure for each of the 9 scenarios:

- Select the parameters of an average performing infiltration trench (according to the results that show average reduction and corresponding uncertainty bounds) of 1x1m cross section. The average performing infiltration trench is an infiltration trench having mean annual runoff reduction from the *MM* model similar to the mean annual runoff reduction from the *SM* model.
- Select a discrete number of unsaturated depths  $h_{us}$  at which  $\beta$  will be computed.
- The parameter  $\beta$  was obtained by parameter optimization using the Model with Mounding. The objective function was the mean annual runoff reduction obtained from the Simple model and shown later in Figure 2. Optimization was done using the *DREAM* optimization software (Vrugt et al., 2009) which employs the Shuffled Complex Evolution Algorithm.

### 3 RESULTS

#### 3.1 Annual stormwater runoff reductions

Figure 2 shows the annual runoff reduction from the Simple Model. These results are considered valid for infiltration trenches without the influence of groundwater, i.e. infiltration trenches that are above a certain distance  $h_{us}$  from the groundwater; later in this section we discuss the effect of the distance  $h_{us}$  on infiltration trench performance. The uncertainty bounds of annual runoff reduction include the effect of inter-annual variation and uncertainty of model input parameters and particularly  $K$ . The effect of inter-annual variation of annual runoff reduction was estimated to influence the mean annual runoff reduction by 10-15%. Locatelli et al. (2015) showed that a soakaway of  $1.9 \text{ m}^3/\text{m}^2$  in a soil with  $K=8.2 \cdot 10^{-7} \text{ m/s}$  has an annual runoff reduction of 68–87% depending on the year. The results show that:

- Infiltration trenches in loamy sand reduce annual runoff by an average of 92-100% with limited uncertainty and thus high confidence. This suggests that infiltration trenches in

- loamy sand, i.e. in soils with an average hydraulic conductivity in the order of  $4 \cdot 10^{-5}$  m/s, that are designed to have at least 4-5 mm of storage depth (S1) and are not influenced by groundwater, have an annual runoff reduction in the order of 92%.
- Infiltration trenches in silt loam reduce annual runoff by an average of 61-73% with a great uncertainty. This suggests that infiltration trenches in silt loam, i.e. in soils with an average hydraulic conductivity on the order of  $1 \cdot 10^{-6}$  m/s, can significantly reduce annual runoff; however their performance is highly uncertain.
  - Infiltration trenches in silty clay loam reduce annual runoff by an average of 38-57% with a large uncertainty. This suggests that infiltration trenches in silty clay loam, i.e. in soils with an average hydraulic conductivity in the order of  $2 \cdot 10^{-7}$  m/s, can contribute up to an average of 57% annual runoff reduction; however their performance is highly uncertain.

Overall results show a relatively small (up to a 20%) increase in annual runoff reduction going from ‘small’ infiltration trenches to ‘large’ ones (from S1 to S3, from S4 to S6 or from S7 to S9). Increasing infiltration trench size from ‘small’ to ‘large’ requires a significant increase in storage depth (see Table 2), e.g. the storage depth in the silty clay loam from scenarios S4 to S6 triples. This suggests that infiltration trenches designed to handle low return period events are likely to be more efficient (*efficiency = annual infiltrated stormwater / storage depth*) for annual runoff reduction than infiltration trenches designed to handle higher return period events. A similar conclusion was also given by Locatelli et al. (2015). Freni et al. (2009) showed that an infiltration unit of  $0.4 \text{ m}^3/100\text{m}^2$  (*storage depth = 4 mm*) in different soils with hydraulic conductivity within  $6.1 \cdot 10^{-6}$  and  $1 \cdot 10^{-4}$  m/s could reduce the 6-year stormwater runoff by 28-80% depending on the local soil conditions.

Figure 3 shows the annual stormwater runoff reductions from the Model with Mounding as a function of the unsaturated depth  $h_{us}$ . The results confirm that the mean annual runoff reduction decreases to 0 as the unsaturated depth decreases to 0. Figure 3 shows that the annual runoff



reduction tends to a constant value (that is the same as the one obtained from the Simple Model) as the unsaturated depth increases above a certain threshold value. The threshold value of unsaturated depth was computed and shown in Table 4 for each scenario. The table shows that infiltration trenches implemented as shown in Figure 1 are not affected by groundwater if the unsaturated depth is above  $\approx 1.5\text{-}3\text{m}$  in loamy sand; above  $\approx 6.5\text{-}8\text{ m}$  in silt loam and above  $\approx 11\text{-}12\text{ m}$  in silty clay loam. There seems to be a decreasing trend in the threshold value within scenarios of the same soils for increasing infiltration trench storage depth (going from S1 to S3, or from S4 to S6). This is likely because the same infiltration trench cross section infiltrates less water as the *Area/Storage ratio* decreases (going from S1 to S3, or from S4 to S6) since less area is drained into a given trench volume; this results in a lower groundwater mound and thus a infiltration trench that can be constructed with a lower unsaturated depth.

366 **The effect of hydraulic conductivity  $K$  variability on annual runoff reduction.**

367 Figure 4 shows the annual stormwater runoff reduction for the  $SM$  and  $MM$  as a function of the  
368 hydraulic conductivity  $K$ . Results are only shown for the  $MM$  when the  $h_{us}$  influences the annual  
369 runoff performance of infiltration trenches, as shown in Table 4.

370 The uncertainty bounds for the  $SM$  (Figure 4a, 4b, 4c) are small and include the effect of  $B$ ,  $H$ ,  $ASR$   
371 variability and inter-annual variations. These results help understanding the uncertainty bounds  
372 shown in Figure 2, and clearly show that the uncertainty was mainly due to the variability of  $K$ . The  
373 uncertainty bounds for the  $MM$  (Figure 4d, 4e, 4f) are wider and include the variability of  $B$ ,  $H$ ,  
374  $L_{drain}$ ,  $h_s$ ,  $ASR$ , inter-annual variations, and are mostly due  $h_{us}$  variability ( $K$  and  $h_{us}$  were found to be  
375 the 2 most influential parameters as shown later in the sensitivity analysis). These results help  
376 understanding the uncertainty bounds shown in Figure 3, and show that  $K$  variability significantly  
377 contributed to such uncertainty.

378 Overall results show great variation of annual runoff reduction in the  $K$  domain except for S1  
379 (Figure 4a). This means that infiltration trenches in loamy sand, i.e. in soils with an average  
380 hydraulic conductivity in the order of  $4 \cdot 10^{-5}$  m/s without the influence of groundwater, are most  
381 likely to give more than 78% annual runoff reductions if infiltration trenches are designed to have at  
382 least 4-5 mm of storage depth (S1 in Table 2).

383 Figure 4b and 4c (S4 to S5), i.e. infiltration trenches in silt loam and silty clay loam without the  
384 influence of groundwater, show annual runoff reduction in the range of 50-100% if the hydraulic  
385 conductivity is above  $K_{mean}$ , however annual runoff reduction is significantly decreased for  $K <$   
386  $K_{mean}$ .

387 Figure 4b, 4c, 4d and 4f, i.e. infiltration trenches in silt loam and silty clay loam, show that the  
388 annual runoff reduction is highly reduced for hydraulic conductivity  $< 1 \cdot 10^{-7}$  m/s.

389 These results suggest that it is relevant to check the spatial variability or site-to-site variability of  $K$ .  
 390 Local infiltration tests are recommended as suggested in many guidelines. Moreover infiltration  
 391 trenches in soils with  $K$  on the order of  $1 \cdot 10^{-7}$  m/s show average annual runoff reductions of 16-70%  
 392 and require large storage depth 36-83 mm, much less efficient than in sandy loam. Bockhorn et al.  
 393 (2014) showed that point measured infiltration rates are often an order of magnitude lower when  
 394 compared to infiltration rates measured in full trench infiltration tests in clay till and sandy clay till.  
 395 This suggests that the infiltration process from infiltration trenches is likely to be a function of  
 396 higher values than the locally measured  $K_{mean}$ . This implies that modeled infiltration rates of an  
 397 infiltration unit using the mean hydraulic conductivity are likely to underestimate trench  
 398 performance.

399 Similar results were found in the literature. Bergman et al. (2011) modelled the performance of 2  
 400 infiltration trenches of  $8 \text{ m}^3$  connected to an impervious area of  $600 \text{ m}^3$  (this corresponds to  $75 \text{ m}^2$   
 401 of impervious area for every  $1 \text{ m}^3$  of storage; or a *storage depth* of 13 mm). For  $K$  in the range of  
 402  $3 \cdot 10^{-7}$  -  $2 \cdot 10^{-6}$  m/s they reported an annual runoff reduction of 94% and for  $K$  in the range of  $3 \cdot 10^{-7}$  -  
 403  $2 \cdot 10^{-6}$  m/s they reported 40%. Freni et al. (2009) modeled an infiltration trench of  $0.4 \text{ m}^3/100\text{m}^2$   
 404 (storage depth = 4 mm) and reported annual stormwater runoff reductions of 28-30% in sandy-  
 405 loam; 34-39% in loamy-sand; 38-66% in sand and 45-80% in gravel.

#### 406 **The effect of $B$ , $h_s$ , $L_{drain}$ variability on annual runoff reduction.**

407 Figure 5 shows the mean annual stormwater runoff reduction as a function of the infiltration trench  
 408 width  $B$  (Figure 5a for  $SM$  and 5b for  $MM$ ), the saturated depth  $h_s$  (Figure 5c), and the draining  
 409 length  $L_{drain}$  (Figure 5d). The uncertainty bounds were not shown in order to make the Figure easier  
 410 to read, but uncertainties are of the same order of magnitude as those presented in Figure 3 and 4.

411 Figure 5a and 5b show that there is an almost linear relationship between annual runoff reduction  
 412 and infiltration trench width  $B$ ; the annual runoff reduction decreases as  $B$  increases. This result can  
 413 be explained by noting that for a given  $ASR$  (*Area/ Storage Ratio*) and  $H$ ; a larger  $B$  means a larger

414 connected impervious area, and a lower ‘wetted area/storage volume ratio’ of the infiltration trench.  
415 Moreover the results from *MM* (Figure 5b) show larger slopes compared to the results from *SM*  
416 (Figure 5a) and this is likely because for a given *ASR* (*Area/ Storage Ratio*) and *H*, infiltration  
417 trench performance is affected by the infiltrated volume: the larger the *B*, the larger the infiltrated  
418 volume, the larger the mounding depth. The influence of the infiltration trench height *H* is not  
419 shown as results are similar to the ones of *B*.

420 Figure 5c shows that the annual runoff reduction increases with saturated depth. This is because the  
421 higher the saturated depth, the higher the aquifer transmissivity and thus the lower the mounding  
422 height and the higher the infiltration rates. Similar observations were also made by Thompson et al.  
423 (2010) and Guo (1998). The loamy sand scenarios (*S1*, *S2* and *S3*) show a higher variation of  
424 annual runoff reduction in the  $h_s$  range of 0-3m than silt loam scenarios (*S4*, *S5* and *S6*), and even  
425 more than silty clay loam scenarios (*S7*, *S8* and *S9*). This is likely because of the model setup, i.e.  
426 as  $h_s$  approaches 0, the groundwater dissipation also becomes 0 (for fixed groundwater gradients)  
427 and thus also the annual runoff reduction tends to 0. Annual runoff reduction is significantly  
428 reduced for a saturated depth  $h_s$  below 2-3m, particularly in sandy loam. This suggests that when  
429 implementing infiltration trenches it is relevant to have a saturated depth of at least couple of meters  
430 and that a higher saturated depth is to be preferred.

431 Figure 5d shows that annual runoff reduction decreases as  $L_{drain}$  increases. This is because the larger  
432 the drainage length the lower the groundwater gradients and thus the higher the mounding and the  
433 lower the annual runoff reduction. The  $L_{drain}$  is shown to be most influential in the sandy loam  
434 scenarios. These results underline the importance of taking into account groundwater drainage when  
435 infiltration trenches are implemented in shallow groundwater areas, particularly in sandy loamy  
436 soils.

437

### 438 **3.2 Single event peak and volume stormwater runoff reductions**

439 Figure 6 shows the single event peak and volume reduction for rain events of 0.5-1 year return  
 440 period using the two models. For the given time series, 0.5-1 year return period events have a  
 441 maximum 10 minute intensity in the range of 33-43 mm/h and a total rainfall volume per event in  
 442 the range of 23-28 mm. Similar trends are observed for both the peak reduction results (Figure 6, a  
 443 to c) and volume reduction (Figure 6, d to f).

444 Infiltration trenches in loamy sand that are designed for a 1 year return period or more (S2 and S3)  
 445 show average peak and volume reduction above 94% if not affected by groundwater (SM), and 62-  
 446 67 % with large uncertainty if close to the groundwater (MM). Infiltration trenches in loamy sand  
 447 can contribute significantly to peak and volume runoff reduction for rain events of 0.5-1 year return  
 448 period, however if the unsaturated depth is  $< 1.5-3$  m the performance can be significantly reduced  
 449 (Figure 3). Infiltration trenches in loamy sand, i.e. in soils with an average hydraulic conductivity in  
 450 the order of  $4 \cdot 10^{-5}$  m/s and without the influence of groundwater, can be designed to significantly  
 451 reduce peak runoff and volume from rain events of 0.5-1 year return period; however their  
 452 performance becomes uncertain for an unsaturated depth less than 1.5-3 m.

453 Infiltration trenches in silt loam show a highly uncertain peak and volume reduction with an  
 454 average of 36-68 % if not affected by groundwater (SM), and 18-37 % if close to the groundwater  
 455 (MM). Infiltration trenches in silt loam can contribute to peak runoff reduction for rain events of  
 456 0.5-1 year return period, however their performance is highly uncertain.

457 Infiltration trenches in silty clay loam show a highly uncertain peak volume reduction with an  
 458 average of 16-43 % if not affected by groundwater (SM), and 5-18 reduction if close to the  
 459 groundwater (MM). Infiltration trenches in silt clay loam can contribute to peak and volume runoff  
 460 reduction for rain events of 0.5-1 year return period, however their performance is highly uncertain  
 461 and quite low also considering the large storage depth required in such a soil.

462 Figure 7 shows the single event peak and volume reduction for rain events of 5-10 year return  
 463 period using the two models. For the given time series it was calculated (not shown) that 5-10 year

464 return period events have a maximum 10 minute intensity in the range of 64-67 mm/h and a total  
465 rainfall volume per event in the range of 46-55 mm. Similar trends are observed when comparing  
466 the peak reduction results (Figure 7, a to c) and volume reduction results (Figure 7, d to f).

467 Results from loamy sand scenarios and *SM*, i.e. for infiltration trenches that are not affected by  
468 groundwater, show that even an infiltration trench designed for a 0.1 y return period (S1) can  
469 contribute with an average 37% reduction of single event runoff volume for 5-10 year return period  
470 events (Figure 7d). Moreover, if infiltration trenches not affected by groundwater are designed to  
471 handle 10 year return period events they can reduce on average 88-95% of the peak and volume  
472 from single events (Figure 1a and 1d). However, infiltration trenches that are affected by  
473 groundwater, i.e. for unsaturated depths <1-5-3m, show single event peak and volume reductions  
474 significantly lower and with a higher uncertainty. Infiltration trenches not affected by groundwater  
475 and in loamy sand, i.e. in soils with an average hydraulic conductivity in the order of  $4 \cdot 10^{-5}$  m/s, can  
476 significantly contribute to reduce peak and runoff volume from rain events of 5-10 year return  
477 period.

478 Results from the silt loam scenarios show that infiltration trenches not affected by groundwater can  
479 contribute with an average 8-54% reduction (*SM*) of single event runoff peak and volume for 5-10  
480 year return period events; and 4-23% (*MM*) if affected by groundwater. Both the *SM* and *MM* show  
481 large uncertainties. Even though infiltration trenches in silt loam might contribute to volume runoff  
482 reduction of 5-10 year return period events, the performance is highly uncertain and to obtain  
483 significant reductions a large storage depth is required (at least 36-50mm of storage depth; S5,  
484 Table 2).

485 Infiltration trenches in silty clay loam show very low peak and volume reductions for 5-10 year  
486 return period events. Some reduction can be achieved by S9, however that scenario requires  
487 infiltration trenches of 67-83 mm storage depth (Table 3) which is large. This suggests that  
488 infiltration trenches in silty clay loam, i.e. in soils with an average hydraulic conductivity in the

order of  $1 \cdot 10^{-7}$  m/s, are not likely to be a good solution for single event peak and volume reduction of events of 5-10 year return period.

Campisano et al. (2011), reported a single event peak flow (for a selected design storm event) reduction of <7% for an infiltration trench of 24 mm storage depth in soils with  $K \leq 10^{-6}$  m/s, and a reduction of 37% in soils with  $K = 10^{-5}$  m/s.

Overall, results show that even if infiltration trenches are designed to handle peak and volume from 5-10 year return period events, their performance is highly uncertain with the exception of infiltration trenches in sandy loam without the influence of groundwater. It can also be seen that when infiltration trenches are designed to handle 5-10 year return period events they must have a large storage depth. These results suggest that infiltration trenches should not be designed with the aim of reducing single events peaks and volume from 5-10 year events. Moreover, infiltration trenches designed to handle more frequent 0.5-1 year return period events can contribute to reduce peak and volume runoff but with high uncertainty. It should be noted that changing the design from a 0.1 year return period design to a 1 year return period requires a 2-3 times increase storage. This suggests that infiltration trenches should be used primarily the aim of reducing annual runoff. Having smaller storage depths also reduces the total infiltrated amount resulting in lower mounds. A similar conclusion was found by Locatelli et al. (2015), who showed that peak flows can be handled more efficiently by detention volumes rather than infiltration trenches.

### 3.3 Sensitivity analysis

The results of the sensitivity analysis for the two models are shown in Figure 8. For simplicity only the results from Scenario 5 are reported since there is not a significant difference in parameter sensitivity for the 9 scenarios. Sensitivity of the single event peak and volume reduction was also determined for Scenario 5 with similar results.

512 The most influential parameter on the annual runoff reduction for the Simple Model is the hydraulic  
513 conductivity  $K$ . *Area/Storage Ratio*,  $B$  and  $H$  have a lower sensitivity scores and are shown to be  
514 negatively correlated, i.e. the higher the parameter the lower the annual runoff reduction. The  
515 sensitivity of the cross section  $B \cdot H$  was similar to that of  $H$  and  $B$  individually, meaning that a  
516 smaller cross section would on average result in higher annual runoff reductions. This is because for  
517 a given *ASR* (*Area/ Storage Ratio*), a larger the cross section  $BH$  results in a larger connected  
518 impervious area and a smaller wetted area/storage volume ratio of the infiltration trench. However  
519 this holds only for long infiltration trenches where the length  $L$  is much larger than the cross  
520 section.

521 The most influential parameters for the Model with Mounding are the hydraulic conductivity  $K$  and  
522 the unsaturated depth  $h_{us}$ , whereas the *Area/Storage Ratio*, the saturated depth  $h_s$ , the length of the  
523 model domain  $L_{drain}$ ,  $B$  and  $H$  have a lower sensitivity score.  $h_s$  is shown to be negatively correlated  
524 to annual runoff reduction, i.e. the higher the saturated depth, the higher the aquifer transmissivity  
525 and thus the lower the mounding height and the higher the infiltration rates.  $L_{drain}$  is also negatively  
526 related to the annual runoff reduction. The extent of the drainage length  $L_{drain}$  influences the  
527 equilibrium depth of the groundwater mound and thus the infiltration capacity from the infiltration  
528 trench, i.e. the higher the drainage length, the higher the height of the mound for a given gradient,  
529 resulting in lower infiltration rates. The soil parameters  $n$ ,  $\theta_s$ ,  $\theta_r$  and  $\alpha$  are shown to be the least  
530 influential parameters for the Model with Mounding. These parameters define the soil moisture  
531 distribution in the unsaturated zone. For example, the parameter  $\alpha$  (the most influential of the  
532 parameters shown in Figure 8) controls the capillary height and its influence on the infiltration  
533 trench performance is expected to increase when the distance between the bottom of the infiltration  
534 trench and the groundwater table is in the same order of magnitude as the capillary height.  $B$  and  $H$   
535 are negatively correlated for the same reasons as mentioned above. Similar observations were  
536 reported by Maimone et al. (2011) and Manglik et al. (2004).



### 537 3.4 Correction factor

538 Figure 9 shows the correction factor as a function of the unsaturated depth. The results show that  
539 the correction factor increases rapidly and that there is a critical unsaturated depth below which the  
540 correction factor cannot influence the infiltration trench performance. This critical depth  $h_{us}$  is  
541 approximately 1-2m in loamy sand and 2-4m in silt loam and silty clay loam (see table 4). However  
542 the magnitude of this critical depth was only derived from a single simulation for each scenario.  
543 Moreover results are affected by model assumptions. For example, as already introduced in Section  
544 2.1, the *MM* model underestimates the performance of infiltration trenches for  $h_{us}$  approaching 0  
545 meaning that the critical depth is underestimated.

546 These results suggest that below a certain value of unsaturated depth the dissipation capacity of the  
547 mound/groundwater becomes the dominant process determining the infiltration capacity from  
548 infiltration trenches, i.e. no matter how big the correction factor is, the infiltration trench  
549 performance is dictated by the mounding/groundwater dissipation capacity. When multiple  
550 infiltration trenches are implemented in the same area this effect becomes even more relevant. This  
551 suggests that when infiltration trenches are designed in an area of shallow groundwater, the design  
552 should be based on the local groundwater dissipation capacity and that proper groundwater drainage  
553 should be the primary consideration.

### 554 3.5 Model limitations

555 The *MM* model assumes that the mound height cannot exceed the infiltration trench bottom. This is  
556 not realistic since in reality it can reach the water level in the infiltration trench. This implies an  
557 underestimation of infiltration rates that increases as the unsaturated depth  $h_{us}$  decreases to 0.

558 The inflow rate  $Q_{in}$  to the infiltration trench was assumed to be the same as the rainfall measured at  
559 the rain gauge, i.e. no initial loss was considered and there was no routing of the runoff from the

560 impervious area to the infiltration trench. This implies a slight underestimation of the performance  
561 of infiltration trenches.

562 The infiltration trench was assumed to be infinitely long, i.e. no-flow in the longitudinal direction,  
563 this implies an underestimation of the infiltration rates as the infiltration trench length  $L$  decreases  
564 to 0. The results presented in the paper underestimate performance for infiltration trenches where  
565 the length  $L$  is in the same order of magnitude as  $B$  and  $H$  (e.g. for near-square trench). Moreover,  
566 this model assumed an initially flat water table. However in reality there are small groundwater  
567 gradients that would produce asymmetric mounding and dissipation rates. However the impact is  
568 expected to be small, especially in areas of small groundwater gradients.

569 The models assumed isotropic and uniform conditions, i.e. the infiltration rate per unit wetted area  
570 of infiltration trench is assumed to be equal to the saturated hydraulic conductivity (i.e. unit-  
571 gradient Darcy flow). However the horizontal hydraulic conductivity is generally higher than the  
572 vertical and heterogeneity and macro-pores are likely to increase the infiltration rates.

573 Clogging was not included into the model. This implies that the simulated performance of the  
574 infiltration trenches is overestimated (Bergman et al., 2011). Clogging is important to be considered  
575 where the periodic maintenance of infiltration systems is not planned.

576 This model assumes infiltration only from a single unit, whereas in reality multiple units would be  
577 installed. Widespread stormwater infiltration increases the groundwater levels and reduces the  
578 infiltration rates compared to our model.

579 In this paper a model with all of the above simplifications is employed, even while knowing that  
580 they cannot be completely justified. This was done because this model is the most realistic one that  
581 is still simple enough to run long-term simulations and complete the statistical analysis presented.  
582 More detailed models would be much more computationally expensive. Our results provide a first  
583 insight and demonstrate that more work is still needed such as simulations of the effects of multiple

584 infiltration trenches placed close to each other and representing groundwater mounds above the  
585 trench bottom in the model.

#### 586 **4 CONCLUSIONS**

587 This paper presents model results that quantify the effects of infiltration trench geometry, soil  
588 variability and the presence of a shallow groundwater table on the hydrological performance of  
589 single infiltration trench. Statistical analysis of continuous long-term simulations of 9 different  
590 scenarios was used to evaluate annual and single event runoff reduction from single infiltration  
591 trenches. Overall results showed that infiltration trenches can reduce annual runoff; that if the soil  
592 hydraulic conductivity is on the order of  $1 \cdot 10^{-7}$  m/s or lower, infiltration trenches might not be a  
593 good solution for handling urban runoff as they require large volumes (36-83 mm) for average  
594 annual runoff reductions of 16-70 %; that it is important to include groundwater drainage in the  
595 design of infiltration trenches; that a saturated thickness of the unconfined aquifer of less than a few  
596 meters can significantly reduce the hydrological performance of infiltration trench; that the more  
597 the infiltrated runoff volume, the more the groundwater mound will reduce the infiltration trench  
598 performance. Results showed that the performance of infiltration trenches is affected by  
599 groundwater when there is an unsaturated depth of less than 1.5-3 m in sandy loam, 6.5-8 m in silt  
600 loam and 11-12 m in silty clay loam.

601 Moreover, this study suggests that infiltration trench should be designed with the aim of reducing  
602 annual runoff and are less effective for single event peak and volume runoff.

603 Finally the results from the correction factor showed that there is an unsaturated depth below which  
604 the infiltration trench performance is governed by the dissipation of the mound. This means that  
605 when designing infiltration trenches very close to the groundwater table the groundwater dissipation  
606 capacity should drive the design process. This suggests that infiltration trench design tools should  
607 consider groundwater, especially in areas with shallow groundwater and that infiltration trench

608 design must be done cautiously when implementing infiltration systems with depth to groundwater  
609 less than the threshold depths indicated for the different soil types.

## 610 **Acknowledgments**

611 The authors thank the Danish Council for Research that financed the present research through the  
612 project BIV (Byer I Vandbalance/Cities in water balance).

613

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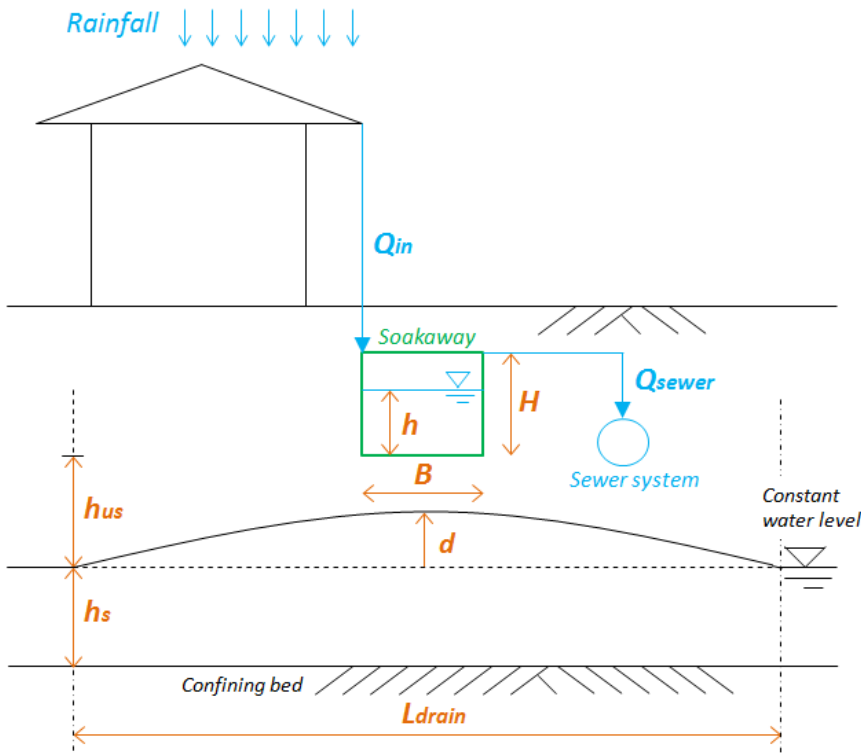
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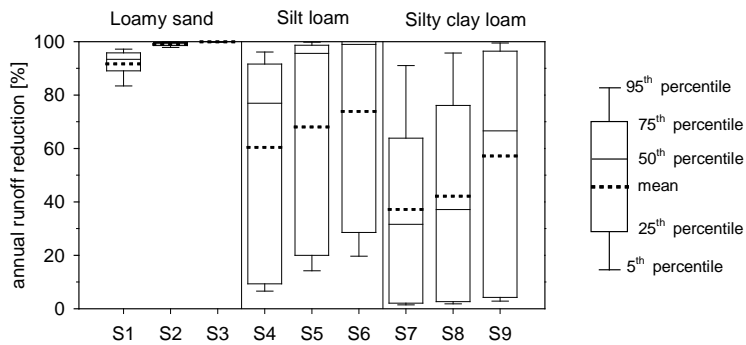
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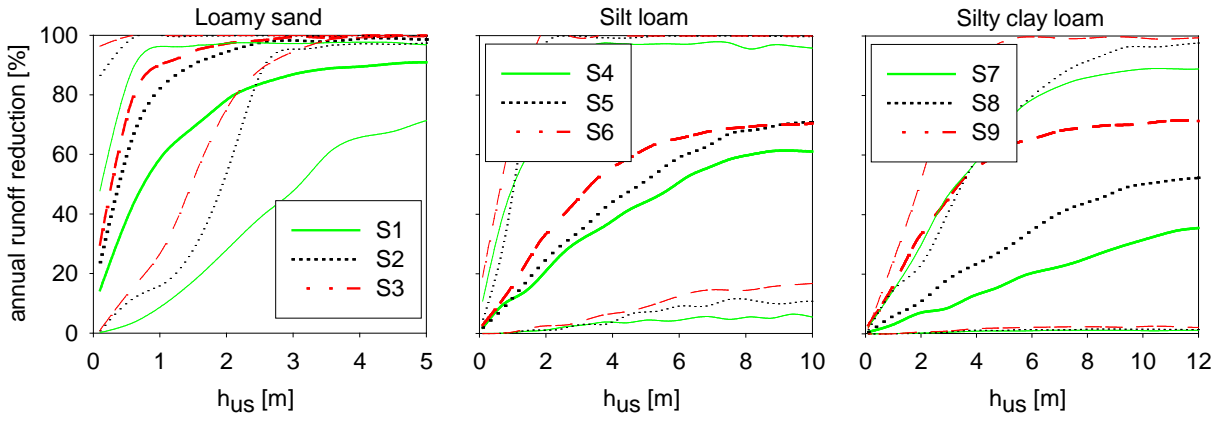
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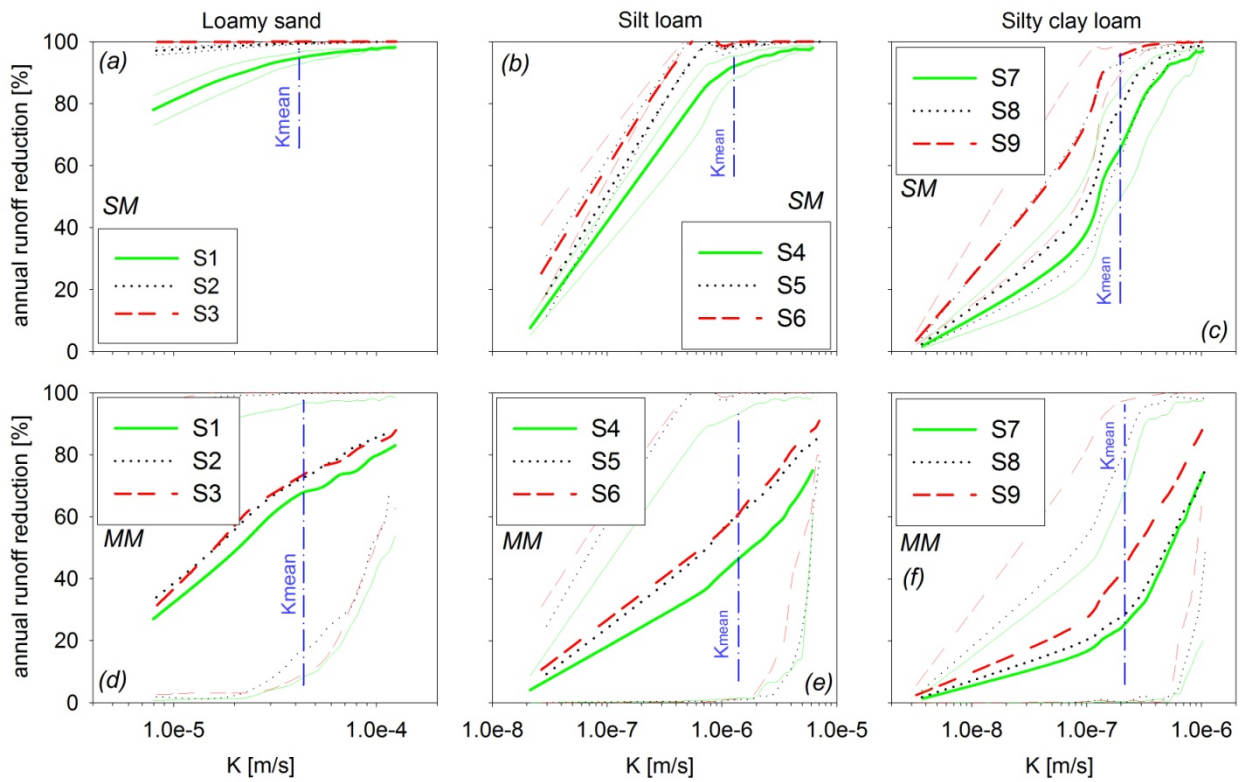
**Figure 1. Sketch of the infiltration trench and the groundwater mound system.**



**Figure 2. Annual stormwater runoff reduction for the 9 scenarios from the Simple Model (SM). The uncertainty bounds of annual runoff reduction include the effect of inter-annual variation and variability of model input parameters, particularly  $K$ .**

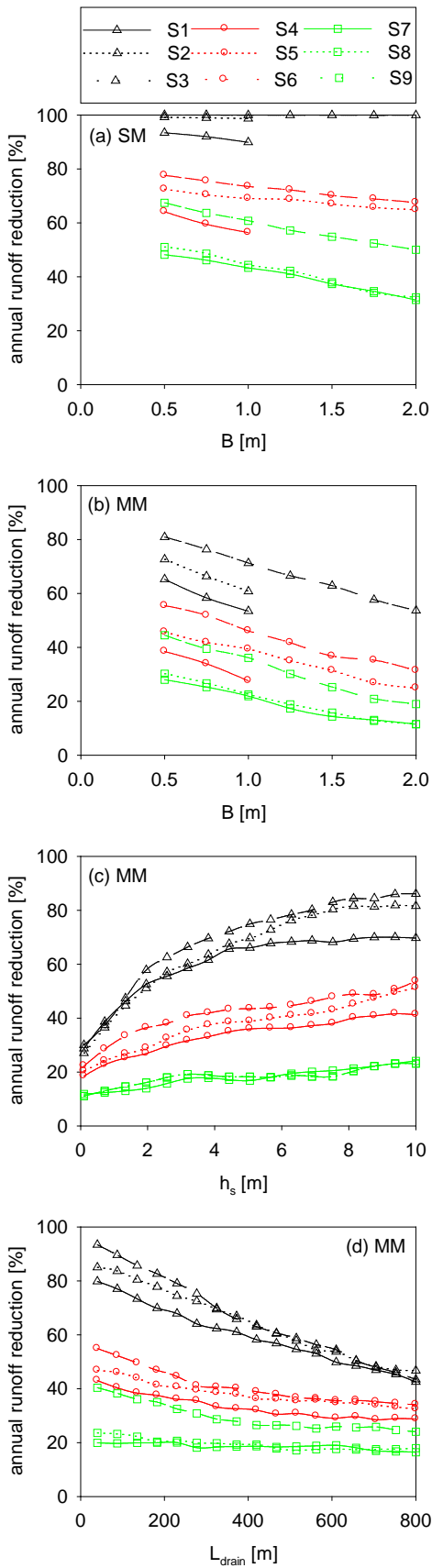


**Figure 3. Annual stormwater runoff reduction as a function of the unsaturated depth. The thicker lines represent the mean, whereas the thinner lines show the 5th and 95th percentiles. The uncertainty bounds of annual runoff reduction include the effect of inter-annual variation and variability of model input parameters, particularly K.**



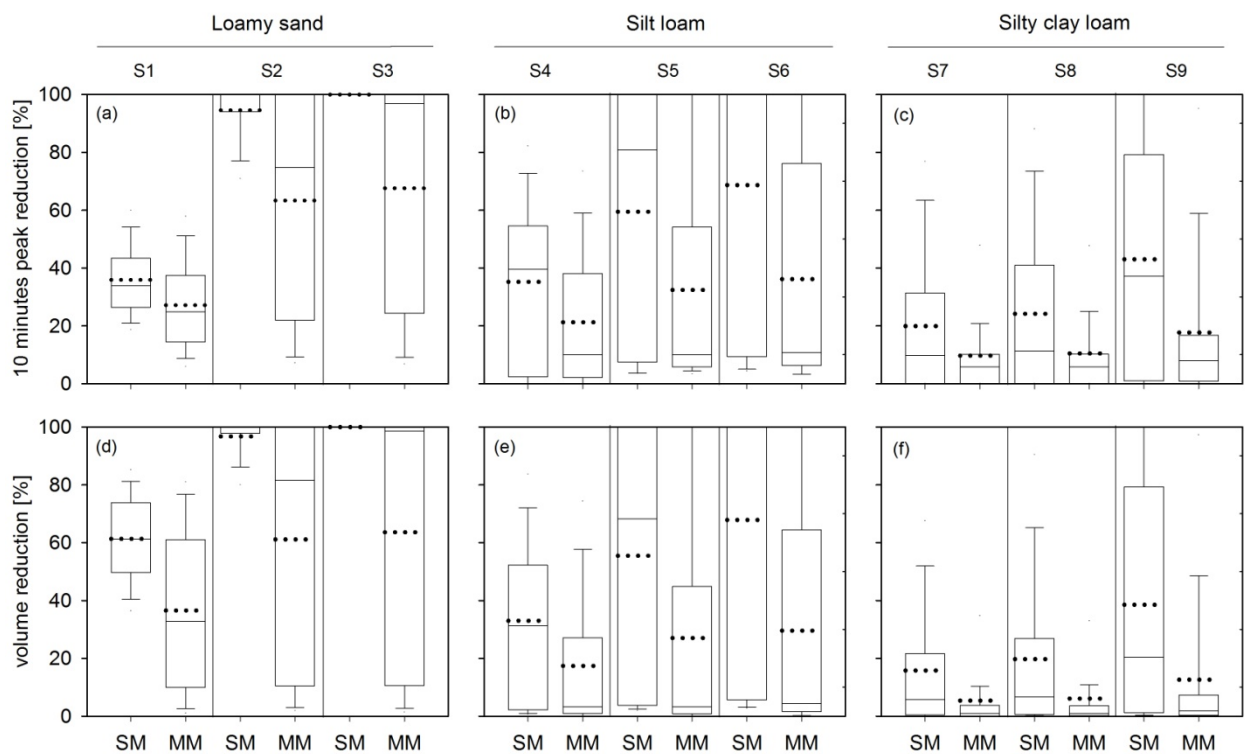
**Figure 4. Annual stormwater runoff reduction as a function of the hydraulic conductivity for the 2 models (SM and MM). The thicker lines represent the mean, whereas the thinner lines show**

753 the 5th and 95th percentiles. The uncertainty bounds of annual runoff reduction include the  
754 effect of inter-annual variation and variability of model input parameters, particularly  $h_{us}$ .  
755



756

757 **Figure 5. Annual stormwater runoff reductions as a function of  $B$ ,  $h_s$  and  $L_{\text{drain}}$ . Simple Model**  
 758 **(SM) and Model with Mounding (MM).**



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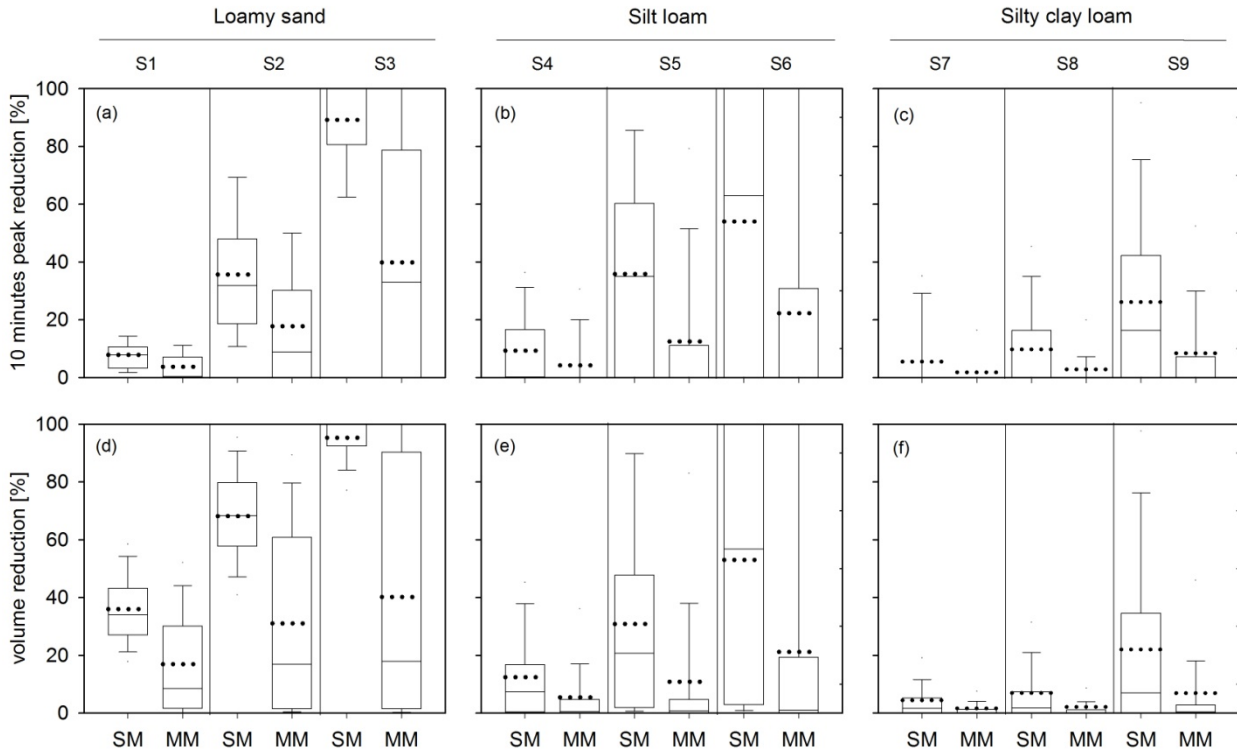
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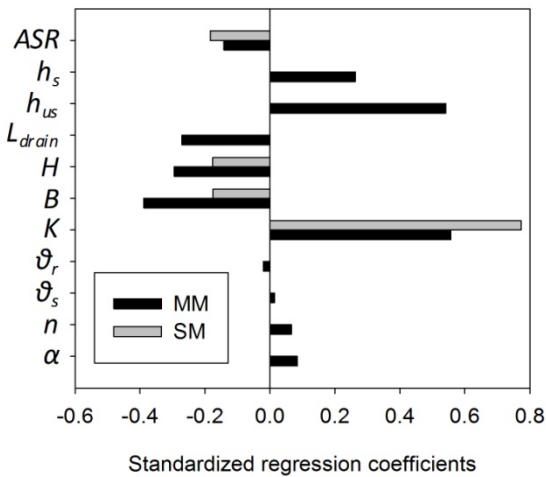
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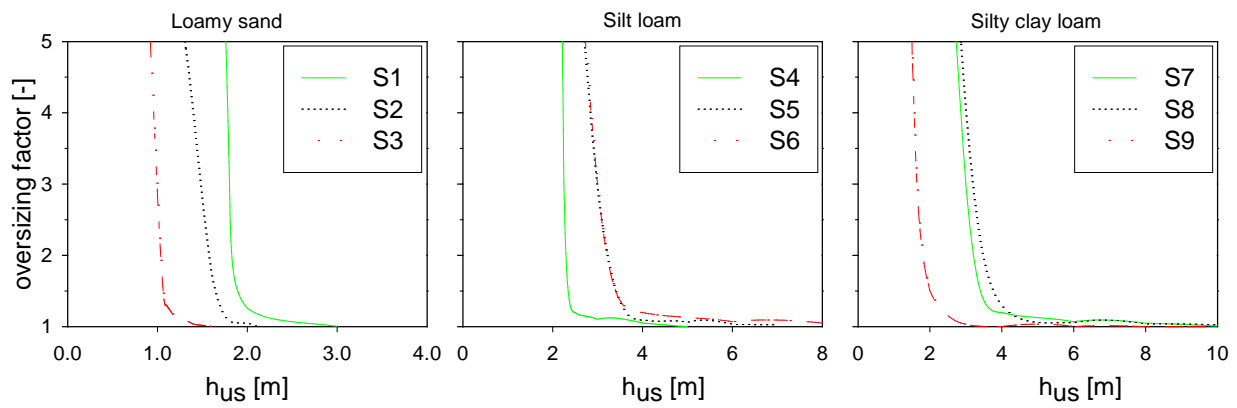
**Figure 6. Single event peak and volume runoff reduction for rain events of 0.5-1 year return period. Simple Model (*SM*) and Model with Mounding (*MM*). The uncertainties in the *SM* are mostly due to *K* variability, whereas in the *MM* they are due to *K* and *h<sub>us</sub>* variability.**



**Figure 7. Single event peak and volume runoff reduction for rain events of 5-10 year return period. Simple Model (SM) and Model with Mounding (MM). The uncertainties in the SM are mostly due to  $K$  variability, whereas in the MM they are due to  $K$  and  $h_{us}$  variability.**



**Figure 8. Standardized regression coefficients illustrating the results of the sensitivity analysis for Scenario 5, based on input defined in Table 3.**



**Figure 9. Correction factor as a function of the unsaturated depth.**



Table 1. Model input parameters

	Parameter	Description	Value	Unit	Simple Model (SM)	Model with Mounding (MM)
Soil parameters	$\alpha$	Van Genuchten parameter		$m^{-1}$		X
	$n$	Van Genuchten parameter		-		X
	$m$	Van Genuchten parameter	$1-1/n$	-		
	$\theta_s$	Saturated moisture content		-		X
	$\theta_r$	Residual moisture content		-		X
	$K$	Saturated hydraulic conductivity		m/s	X	X
Infiltration trench parameters	$L$	Length of the infiltration trench		m		
	$B$	Width of the infiltration trench		m	X	X
	$H$	Height of the infiltration trench		m	X	X
	$\phi$	Porosity of the filling material		-		
	ASR (Area/ Storage Ratio)	'Connected impervious area' / 'Infiltration trench volume'		$m^2/m^3$	X	X
Unsaturated and saturated zone	$h_{us}$	Thickness of the unsaturated zone		m		X
	$h_s$	Thickness of the saturated zone		m		X
Draining distance	$L_{drain}$	Length of the model domain		m		X

Table 2. Model scenarios

Scenario	Description	Infiltration trench design			B ** [m]	H ** [m]	$h_{us}$ ** [m]	$h_s$ ** [m]	$L_{drain}$ ** [m]
		Design return period [years]*	Area/Storage Ratio [ $m^2/m^3$ ]	Storage depth [mm]					
S1	Small infiltration trench in loamy sand	0.1	200-230	4-5	0.5-1	0.5-1	0-5	1-10	40-800
S2	Medium infiltration trench in loamy sand	1	75-90	11-13	0.5-1	0.5-1	0-5	1-10	40-800
S3	Large infiltration trench in loamy sand	10	35-45	22-29	0.5-2	0.5-1	0-5	1-10	40-800
S4	Small infiltration trench in silt loam	0.1	55-70	14-18	0.5-1	0.5-1	0-10	1-10	40-800
S5	Medium infiltration trench in silt loam	1	20-28	36-50	0.5-2	1	0-10	1-10	40-800
S6	Large infiltration trench in silt loam	5	14-18	56-71	0.5-2	1	0-10	1-10	40-800
S7	Small infiltration trench in silty clay loam	0.1	30-40	25-33	0.5-2	0.5-1	0-15	1-10	40-800
S8	Medium infiltration trench in silty clay loam	0.2	20-28	36-50	0.5-2	1	0-15	1-10	40-800

S9	Large infiltration trench in silty clay loam	1	12-15	67-83	0.5-2	1	0-15	1-10	40-800
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\*According to Danish standards (Petersen et al., 1995)  
 \*\* Uniform distribution

**Table 3. Soil input parameters**

	Loamy sand		Silt loam		Silty clay loam	
	<i>Mean</i>	<i>STD</i>	<i>Mean</i>	<i>STD</i>	<i>Mean</i>	<i>STD</i>
$\alpha [m^{-1}]$ *	12.4	4.3	2.0	1.2	1.0	0.6
$n$ *	2.28	0.27	1.41	0.12	1.23	0.06
$\theta_s$ *	0.41	0.09	0.45	0.08	0.43	0.07
$\theta_r$ *	0.057	0.015	0.067	0.015	0.089	0.009
$K [m/s]$ **	$4.05 \cdot 10^{-5}$	$3.16 \cdot 10^{-5}$	$1.25 \cdot 10^{-6}$	$3.42 \cdot 10^{-6}$	$1.94 \cdot 10^{-7}$	$5.3 \cdot 10^{-7}$

\* Normal distribution  
 \*\* Log-Normal distribution (non-transformed *Mean* and *STD*)

**Tabel 3. Threshold value of unsaturated depth for the model scenarios.**

Soil type	Scenario	Infiltration trench design return period [y]	Threshold unsaturated depth $h_{us}$ [m]
Loamy sand	S1	0.1	3
	S2	1	2
	S3	10	1.5
	S4	0.1	8
Silt loam	S5	1	8
	S6	5	6.5
	S7	0.1	12
Silty clay loam	S8	0.2	12
	S9	1	11